Electromagnetic Form Factors of the Nucleon

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Abstract. We reanalyze the world data on the electromagnetic form factors of the nucleon. The calculations are performed in the framework of an algebraic model of the nucleon combined with vector meson dominance.

I INTRODUCTION

The electromagnetic form factors of the nucleon and its excitations (baryon resonances) provide a powerful tool to investigate the structure of the nucleon [1]. These form factors can be measured in electroproduction as a function of the four-momentum squared $q^2 = -Q^2$ of the virtual photon. Especially the transition to the region of high momentum transfer, for which the methods of perturbative QCD apply, is currently of much interest [2].

In this contribution we present an analysis of the world data for the elastic form factors $G^{p/n}_{E/M}$. Our method is a combination of a recently introduced algebraic model of the nucleon [3] and vector meson dominance.

II ALGEBRAIC MODEL

The algebraic approach provides a unified treatment of various constituent quark models [3], such as harmonic oscillator quark models and collective models. In this contribution we employ a collective model of the nucleon in which baryon resonances are interpreted as vibrational and rotational excitations of an oblate top. There are two fundamental vibrations: a breathing mode and a two-dimensional vibrational mode, which are associated with the $N(1440)P_{11}$ Roper resonance and the $N(1710)P_{11}$ resonance, respectively. The negative parity resonances of the second resonance region are interpreted as rotational excitations. Since each vibrational mode has its own characteristic frequency,

this collective model has no problem with the relative energy of the Roper resonance with respect to the negative parity resonances.

In [4] we studied the elastic electromagnetic form factors of the nucleon. These calculations include anomalous magnetic moments for the proton and the neutron, as well as a flavor dependent distribution functions of the charge and magnetization. Supposedly, the anomalous magnetic moments and the flavor dependence arise as effective parameters, since the coupling to the meson cloud surrounding the nucleon was not included explicitly. According to [4] the electric and magnetic form factors of the nucleon, when folded with a distribution of the charge and magnetization, can be expressed in terms of a common intrinsic dipole form factor

$$\begin{aligned} G_E^p(Q^2) \;&=\; G_M^p(Q^2) \;=\; g(Q^2) \;=\; 1/(1+\gamma Q^2)^2 \;, \\ G_M^n(Q^2)/G_M^p(Q^2) \;&=\; -2/3 \;, \qquad G_E^n(Q^2) \;=\; 0 \;. \end{aligned} \tag{1}$$

Note that the Sachs form factors of Eq. (1) do not contain anomalous magnetic moments nor involve flavor dependent distribution functions. In order to study the coupling to the meson cloud we express the Sachs form factors in terms of the isoscalar and isovector Dirac ($F_1^{S/V}$) and Pauli ($F_2^{S/V}$) form factors

$$\begin{aligned} F_1^S(Q^2) \;=\; g(Q^2)\,\frac{1+\frac{1}{3}\tau}{1+\tau} \;, \qquad F_1^V(Q^2) \;=\; g(Q^2)\,\frac{1+\frac{5}{3}\tau}{1+\tau} \;, \\ F_2^S(Q^2) \;=\; -F_2^V(Q^2) \;=\; -\frac{2}{3}\,g(Q^2)\,\frac{1}{1+\tau} \;, \end{aligned} \tag{2}$$

with $\tau = Q^2/4M^2$.

III MESON CLOUD COUPLINGS

The effects of the meson cloud surrounding the nucleon are taken into account in a similar way as in [5], *i.e.* by including the coupling to the isoscalar vector mesons ω and ϕ and the isovector vector meson ρ. These contributions are studied phenomenologically by parametrizing the Dirac and Pauli form factors as

$$\begin{aligned} F_1^S(Q^2) &= g(Q^2)\,\frac{1+\frac{1}{3}\tau}{1+\tau}\left[\beta^S + \beta_\omega\,\frac{m_\omega^2}{m_\omega^2+Q^2} + \beta_\phi\,\frac{m_\phi^2}{m_\phi^2+Q^2}\right] \;, \\ F_1^V(Q^2) &= g(Q^2)\,\frac{1+\frac{5}{3}\tau}{1+\tau}\left[\beta^V + \beta_\rho\,\frac{m_\rho^2}{m_\rho^2+Q^2}\right] \;, \\ F_2^S(Q^2) &= -\frac{2}{3}\,g(Q^2)\,\frac{1}{1+\tau}\left[\alpha^S + \alpha_\omega\,\frac{m_\omega^2}{m_\omega^2+Q^2} + \alpha_\phi\,\frac{m_\phi^2}{m_\phi^2+Q^2}\right] \;, \\ F_2^V(Q^2) &= \frac{2}{3}\,g(Q^2)\,\frac{1}{1+\tau}\left[\alpha^V + \alpha_\rho\,\frac{m_\rho^2}{m_\rho^2+Q^2}\right] \;. \end{aligned} \tag{3}$$

The large width of the ρ meson ($\Gamma_\rho = 151$ MeV) is taken into account by making the replacement [5]

$$\frac{m_\rho^2}{m_\rho^2 + Q^2} \rightarrow \frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{m_\rho^2 + Q^2 + (4m_\pi^2 + Q^2)\Gamma_\rho \alpha(Q^2)/m_\pi} \tag{4}$$

with

$$\alpha(Q^2) = \frac{2}{\pi}\left[\frac{4m_\pi^2 + Q^2}{Q^2}\right]^{1/2} \ln\left(\frac{\sqrt{4m_\pi^2 + Q^2} + \sqrt{Q^2}}{2m_\pi}\right) . \tag{5}$$

The coefficients $\beta^{S/V}$ and $\alpha^{S/V}$ are determined by the electric charges and the magnetic moments of the nucleon, respectively.

For small values of the momentum transfer the Dirac and Pauli form factors are dominated by the meson dynamics and reduce to a monopole form, whereas for high values they show the Q^2 dependence as predicted by perturbative QCD

$$F_1^{S/V} \sim 1/Q^4 , \qquad F_2^{S/V} \sim 1/Q^6 . \tag{6}$$

IV RESULTS

Recently, the electromagnetic form factors of the nucleon have been remeasured (or reanalyzed) [6,7]. In Figs. 1–4 we show a compilation of the world data on the electromagnetic form factors of the nucleon. In the present calculation the coefficients β_M and α_M (with $M = \rho$, ω, ϕ) and the scale parameter γ in the dipole form factor $g(Q^2)$ are determined in a simultaneous fit to all four electromagnetic form factors of the nucleon with $Q^2 \leq 10$ (GeV/c)^2 (solid lines, Fit 1). As usual, the form factors are scaled by the standard dipole fit $F_D = 1/(1 + Q^2/0.71)^2$. The oscillations around the dipole values are due to the meson cloud couplings. The magnetic form factors show an interesting behavior. Whereas G_M^p first decreases with respect to the dipole, the new measurements of G_M^n show an increase with respect to F_D [7,8]. This behavior is reproduced by the present calculation.

The electric form factor of the neutron is the least known. Unlike for the proton, the Rosenbluth separation of G_E^n from G_M^n for a neutron target is difficult for all values of Q^2: for small Q^2 because of the small size of G_E^n compared to G_M^n, and for large Q^2 because the magnetic component dominates both the angular dependent and angular independent term in the cross section. For this reason we have carried out a second fit, in which G_E^n is excluded from the fitting procedure and replaced by the proton and neutron charge radii (dashed lines, Fit 2). In this calculation the neutron charge radius (the

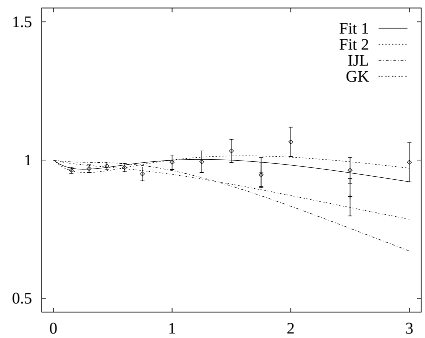

FIGURE 1. Proton electric form factor G_E^p/F_D as a function of Q^2 in (GeV/c)^2.

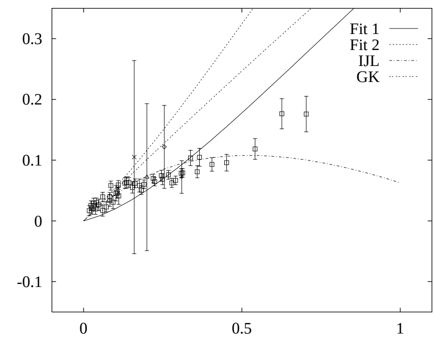

FIGURE 2. Neutron electric form factor G_E^n/F_D.

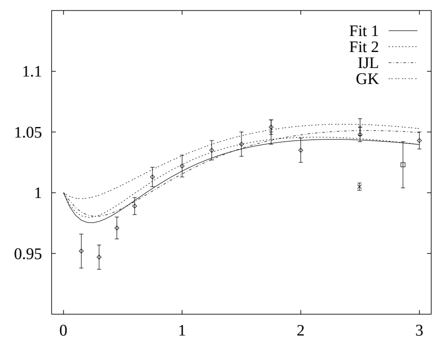

FIGURE 3. Proton magnetic form factor $G_M^p/\mu_p F_D$.

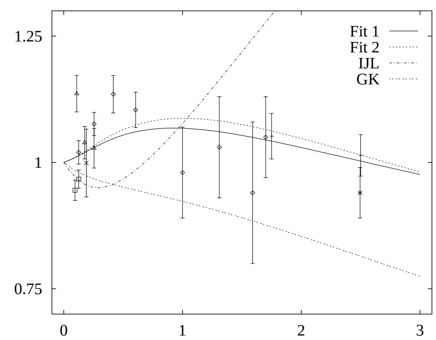

FIGURE 4. Neutron magnetic form factor $G_M^n/\mu_n F_D$.

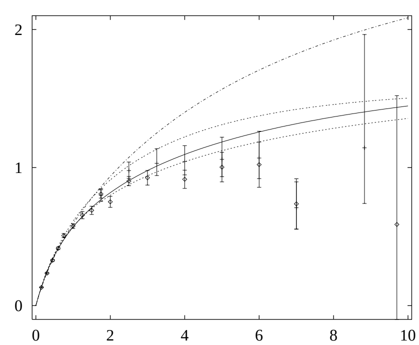

FIGURE 5. Ratio of proton form factors $Q^2 F_2^p/F_1^p$.

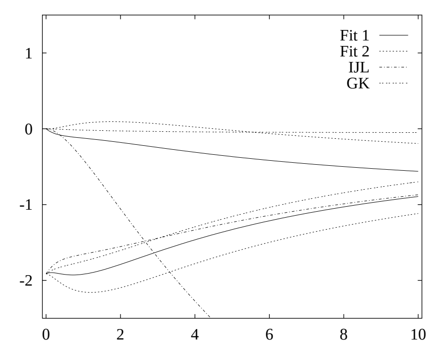

FIGURE 6. Neutron form factors F_1^n/F_D and F_2^n/F_D.

slope of G_E^n in the origin) is reproduced, but the existing data for G_E^n are overpredicted. The changes for the other form factors are minor.

In Fig. 5 we show the scaling property of the proton form factors: $Q^2 F_2^p/F_1^p \sim 1$. The Dirac and Pauli form factors of the neutron are presented in Fig. 6. Since in our calculations the Dirac form factor is small $F_1^n \approx 0$, we find $G_E^n \approx -\tau G_M^n$. For $\tau \approx 1$ ($Q^2 \approx 4M^2$) the electric and magnetic form factor become comparable in size. The same effect was pointed out in [9].

For comparison we also show the results of two other calculations: the vector meson dominance model of Iachello, Jackson and Lande [5] (dash-dotted lines, IJL), and a hybrid model (interpolation between vector meson dominance and pQCD) by Gari and Krümpelmann [9] (dash-dashed lines, GK).

V CONCLUSIONS

We have presented a simultaneous analysis of the elastic electromagnetic form factors of the nucleon in the context of an algebraic model of the nucleon combined with vector meson dominance. For a phenomenological approach (as the present one) a good data set is a prerequisite. Whereas the proton form factors are relatively well known, there is still some controversy about the neutron form factors. New measurements of the polarization asymmetry in which the ratio of the electric and magnetic form factor of the neutron is extracted [7,10] may help to clarify the experimental situation.

In addition to the elastic form factors discussed in this contribution, there is currently much interest in the inelastic transition form factors [2]. We plan to extend the present approach to include the resonance form factors as well, in order to analyze all electromagnetic form factors within the same framework.

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